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ON THE NATURE OF THE INHOMOGENOUS STRUCTURE OF INTERPLANETARY PLASMA

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SUMMARY

One of the possible mechanisms is discussed of inhomogenous structure formation in interplanetary plasma. This mechanism is based on plasma instability on account of temperature anisotropy in interplanetary plasma. Various types of instabilities are considered with their spectra as a function of the value of parameter β applicably to different regions of interplanetary plasma.

It is pointed out that smaller inhomogeneities, of $\sim$ 20 - 100 km exist side by side with the observed ones with characteristic dimensions of $\sim$ 300 - 600 km, namely in remote regions from the Sun, exceeding 1 a.u. Attention is drawn to the appropriateness and advisability of of such small-scale inhomogeneities' observations.

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1. The radioastronomical method of investigation of Sun's supercorona and of interplanetary plasma ("translucence" method) resulted in 1954 in the discovery of their essentially inhomogenous structure. It was established that there is an inhomogeneity of electron density inducing radiowave scattering. [1, 2]. By 1963 the existence of inhomogenous structure could be "traced" to distances $\sim 60\ R_{\odot}$ from the center of the Sun; however, a substantial uncertainty existed in the determination of inhomogeneity parameters [3 - 5]. This was related to the fact that in the "translucence" method the directly measured quantity is the angle of radiowave scattering, with the help of which the combination of values

$$\frac{(\Delta N)^2}{l}, \qquad (1)$$

is computed, where ΔN is the excess of electron concentration in inhomogeneities above the average value, l is the effective dimension of inhomogeneities. The discovery of anisotropy in 1957 permitted to conclude that electron inhomogeneities have an elongated shape and are mostly oriented in a direction close to radial relative to the Sun.

(*) O PRIRODE NEODNORODNOY STRKTURY MEZHPLANETNOY PLAZMY

Simultaneous observations of Crab Nebula on interferometers with three differently oriented bases allowed us to establish in periods of its rapprochement with the Sun, that the shape of the scattered source in the pictorial plane is close to elliptical, with axes' ratio equal to about 1 for $r/R_\odot \lesssim 10$; but for $r/R_\odot > 10$ it becomes equal to about 1/2 and preserves this value constant over a broad region of distances (to 40 $R_\odot$) [5b]. These averaged results allow us to draw the conclusion about the shape of the scattering inhomogeneities and to assume the existence of isotropic inhomogeneities in the region of distances $r/R_\odot \lesssim 10$ and of radially elongated ones in the region $r/R_\odot > 10$.

Discovered in 1963 were the quasars, i. e. radiosources with extremely small angular dimensions $\lesssim 1''$, woing to which it became possible to apply another radioastronomical method of study of interplanetary plasma, and namely, the method of sources' radio-scintillation. Observations by this method began to take place in 1964 and resulted in the possibility of tracing the inhomogenous structure of interplanetary plasma in the region of distances (80 - 260)$R_\odot$ [6 - 8]. The extension of the scintillation method to the centimeter wave region in 1966 permitted the tracing by this method of the entire interval of distances from 20 to 260 $R_\odot$ [9 - 11].

In the latter method the measured quantities are τ-periods of scintillations

$$\tau = \frac{L}{v}, \tag{2}$$

where L is the scale of Earth's diffraction pattern (*), v is the motion velocity of inhomogeneities and F is the measure of scintillations:

$$F = \frac{\overline{I^2} - (\bar{I})^2}{(\bar{I})^2} \tag{3}$$

For $\overline{\Delta\Psi^2} < 1$ and the wave parameter $D \gtrsim 1$ (which is fulfilled in the indicated experiments) the latter is linked with the parameters of the scattering medium by way of the correlation [13]

$$F = 2(\overline{\Delta\Psi})^2 \tag{4}$$

in which the values of ΔN and l are part of the combination

$$F \propto (\Delta N)^2 l. \tag{5}$$

Observations of radio-scintillations have shown that the histograms of scintillation periods vary little in the (80 - 260) $R_\odot$ interval of distances from the center of the Sun [8, 9]. The significant constance pf the scintillation period points to the invariability of average dimensions of electron inhomogeneities froma broad range of distances from the Sun. From observations of scintillation periods estimates were made for the spectrum of inhomogeneities; however, the values of parameter l are essentially dependent on the motion velocity of inhomogeneities, which could not be measured until 1966 [14]. Observation of motion of inhomogeneities by way of time lag measurement

(*) In case when $\overline{(\Delta\Psi)^2} < 1$, $\overline{((\Delta\Psi)^2}$ being the root-mean-square wave phase invasion in the layer at the expense of inhomogeneities), which takes place in conditions of interplanetary plasma, the dimension is $L = l$ [1].

of the corresponding scintil ations at three different points allowed us to determine the velocity vector of the inhomogeneities. The most characteristic velocities of predominantly radial motions were found to be equal to 250-350 km/ /sec [14], i. e. this velocity was of the same order as that of charged particle flux measured on rockets [15]. This allows the assumption that the inhomogeneities of interplanetary plasma are one of the solar wind components, mainly mov ving together with the plasma flux.

The data on scintillation period and on the motion velocity of inhomogeneities provide an unambiguous determination of l, i. e. the scale of inhomogeneities. Comparison with the data obtained by "translucence"methods shows that the spectrum of scattering inhomogeneities in the region $4.5 \leqslant r/R_0 \leqslant 260$ is located mainly in the interval

$$100 \text{ km} \lesssim l \lesssim 1000 \text{ km} \tag{6}$$

with a characteristic dimension of l at a distance $\simeq 100\ R_\odot$, equal to ~ 800 km according to Vitkevich's estimates [8, 14] and 200 - 300 km according to Hewish [16].

In its turn, the value of l allows us to compute ΔN with the aid of relations (1) and (5). Observation data on radiowave scattering, obtained by duf- ferent authors according to scintillations, are utilized in the work [17], and the values of ΔN are brought up for various distances from the Sun. The values of electron concentration ΔN near the Earth's orbit were found to be equal to ΔN (0.1 - 0.05) cm^{-3}. Comparison of the obtained values of ΔN with the existing data on average concentration of electrons obtained by Blackwell's optical measurements [18] shows that the relative values of electron concentration small-scale inhomogeneities (6) constitute about 1.5 - 4 percent [17].

Therefore, the existence of inhomogenous structure of interplanetary plasma may presently be considered as reliably established.

2. Attempts have already been made in literature to explain the inhomogeneity of interplanetary plasma as a consequence of development in it of different kinds of instabilities. We do not intend to dwell here upon the reliability of either instability mechanism of interplanetary plasma, but we should like to draw attention if only to one of them, which stems from experimental facts. Namely, rocket investigations conducted in 1966 allowed the obtaining of very important information on the properties of interplanetary plasma. Measurements carried out on the rocket PIONEER-6 established the existence of a s gnificant anisotropy in the distribution of plasma particles by velocities near the Earth's orbit [19] (the trajectory of PIONEER-6 was close to Earth's orbit): the temperature $T_\parallel$ in the direction of the magnetic field was found to be about 5 times higher than in the perpendicular direction $T_\perp$, whereupon near the Earth's orbit $T_\parallel \sim 10$ °K. This experimentally established anisotropy of plasma, as a possible cause of its instability, is precisely the fact to which we wish to draw attention.

The instability of plasma with anisotropic temperature is studied in literature at sifficient length [20 - 23]. From these investigations it is well known that plasma is found to be unstable for as small an anisotropy as desirable $T_\perp \neq T_\parallel$.

The instability is manifest in the onset of excitation of longwave and shortwave oscillations in the plasma. Thus, in a collisionless plasma in the absence of a magnetic field, or, to be more precise, for

$$\beta = \frac{8\pi N T_{\parallel}}{B_0^2} \gg 1\Big)_{Le}$$

there takes place for $T_{\parallel} > T_{\perp}$ an aperiodic build-up of oscillations propagating nearly perpendicularly to the magnetic field (direction of maximum temperature). This means that the perturbations corresponding to such oscillations must extended in the longitudinal direction at least by 2 to 3 times The increment of instability development is of the order [20]

$$\gamma = \frac{\omega_{Le} k v_{T_{\parallel}}}{\sqrt{k^2 c^2 + \omega_{Le}^2}}, \tag{7}$$

where k is the wave number (or the inverse dimension $k \sim \pi/l$ of the perturbation),

$$v_{T_{\parallel}} = \sqrt{\frac{T_{\parallel}}{m}}$$

is the thermal velocity of plasma electrons, and

$$\omega_{Le} = \sqrt{\frac{4\pi N e^2}{m}}$$

is the Langmuir frequency.

The conditions of applicability of formula (7) $\gamma \gg k v_{T_{\perp}}, \nu_e$ determine the dimensions of perturbations that may develop in the plasma:

$$\sqrt{\frac{T_{\perp}}{T_{\parallel}}} \frac{\pi c}{\omega_{Le}} < l < \frac{\pi v_{T_{\parallel}}}{\nu_e}. \tag{8}$$

Here ν_e is the collision frequency of electrons.

When $\beta \sim 1$, the influence of the magnetic field upon the character of instability becomes substantial. In this case the development of instability is possible if

$$\frac{T_{\parallel}}{T_{\perp}} > \frac{1}{2}\left(1 + \frac{v_A^2}{v_{\perp i}^2}\right), \tag{9}$$

where $v_A = \sqrt{\frac{B_0^2}{4\pi N M}}$ is the Alfvén velocity, whereupon the increment of its development is of the order [21, 22]

$$\gamma \lesssim \sqrt{2} k v_{T_{\parallel}} \sim \sqrt{2} k \sqrt{\frac{T_{\parallel}}{M}}. \tag{10}$$

The perturbations linked with the development of such an instability are also extended longitudinally, though to a lesser degree than the above considered (for $\beta \gg 1$). From the condition of applicability of formula (10)

$$\Omega_i = \frac{eB_0}{Mc} \gg \gamma \gg \nu_i$$

we find that the dimension of unstable perturbations in the plasma are:

$$\frac{\pi}{\Omega_i}\sqrt{\frac{2T_\parallel}{M}} < l < \frac{\pi}{\nu_i}\sqrt{\frac{2T_\parallel}{M}}. \tag{11}$$

Finally, for $\beta \ll 1$, development of slow cyclotron anisotropic instability is possible with maximum increment [23]:

$$\gamma = \frac{\sqrt{\pi}\omega_{Li}T_\perp}{\sqrt{2T_\parallel Mc^2}},\ e^{-\frac{B_0^2}{8\pi NT_\parallel}\frac{T_\parallel^2}{(T_\perp - T_\parallel)^2}}. \tag{12}$$

The length of the wave of maximum rate of building-up oscillations correspomds to perturbations with dimension

$$l \approx \frac{\pi v_A}{\Omega_i}\left(1 - \frac{T_\perp}{T_\parallel}\right)^{-1} \tag{13}$$

3. We shall attempt to relate the anisotrpic plasma instabliity with the observed inhomogeneities. Let us note, first of all, that the anisotropy of interplanetary plasma may be considered as experimentally established only in the region of the Earth's orbit (trajectory of Pioneer-6). According to the recently completed work [24], the plasma anisotropy must be maximum precisely in the Earth's orbit region. Thus we shall consider this region first of all. In it $\beta \sim 1$ and $T_\parallel / T_\perp \sim 5$, which assures the fulfillment of the instability condition (9). Taking into account that in the region of the Earth's orbit $N \sim 1\ cm^{-3}$, $\Omega_i \sim 2\ 10^{-1}$ 1/sec, $\nu_i \sim 10^{-6}$ 1/sec, it then follows from inequalities (11) that the dimensions of the observed inhomogeneities must be within the range

$$300\ \text{км} < l < 10^8\ \text{км}. \tag{14}$$

Since the increment of instability development (10) rises in this region with the increase of <u>k</u>, it appears that the small-scale inhomogeneities $l \sim 300$ км are the most probable, which agrees well with the experiment (see above).

In the region behind the Earth;s orbit $\beta \ll 1$, and if there exists a temperature anisotropy $T_\parallel > T_\perp$, we must take advantage of inequalities (8) for the estimate of inhomogeneity dimensions. Taking into account that in this region $N < 1\ 1/cm^3$, $T \sim 10^5$°K and $\nu_e \sim 4\ 10^{-5}$ 1/sec, we have

$$20\ \text{km} < l < 10^8\ \text{km} \tag{15}$$

Here too most probable are the small-scale inhomogeneities. However, on account of their rapid oscillations

$$\left(\omega \sim \gamma \sim \omega_{Le} \frac{v_{Te}}{c} \sim 10\text{—}10^2\ 1/\text{sec} \right)$$

the latter, particularly small-scale, cannot be observed if their period of oscillations is significantly smaller than the observation time $\tau \sim (0.5 - 0.9)$ sec. For the inhomogeneities to be observable it is necessary that $\tau \sim 1/\gamma$. This inequality is fulfilled for inhomogeneities with

$$l > \frac{v_{Te}}{2\pi} \sim 100 \quad \text{км.}$$

It should be noted that, as the observation time decreases, smaller-scale inhomogeneities must become observable in the region beyond the Earth's orbit. namely those that are forecast by theory on the condition that plasma is endowed with sufficiently temperature anisotropy $T_\parallel > 2T_\perp$. This is why the experimental investigation of this region of interplanetary plasma may serve as criterion of validity of uor hypothesis on the nature of inhomogeneities.

Finally, in the region before the orbit of the Earth, where $\beta \ll 1$, the observed inhomogeneities may also be linked with plasma anisotropic instability. The most probable dimension of such instabilities, determined from formula (13), is $l \sim 100 - 300$ km (note that in this region the quantity Ω_i/v_A varies rather slowly with distance), also agrees well with the experiment.

Let us discuss in conclusion the question of values of density fluctuations $\Delta N/N$ as the anisotropic instability develops in the plasma. This question is the subject of study of nonlinear plasma oscillations. At the present time such a theory is far from completion and it can amswer this question only in case of weak anisotropy, when $|T_\parallel - T_\perp| \ll T_\parallel$. At the same time, in the region of weak fields (for >1) theory gives $\Delta N/N \sim v_{Te}{}^2/c^2 \sim 10^{-5}$, while in the region of intense fields

$$(\beta \ll 1) - \frac{\Delta N}{N} \sim \frac{v_A{}^2}{c^2} \sim 10^{-7} - 10^{-4}.$$

These values are much below the experimentally observable ones $\Big($ let us recall that

$$\left.\left(\frac{\Delta N}{N}\right)_{\text{experim.}} \sim 10^{-2}\right),$$

but here there is nothing particularly surprising, for theory considers here only the case of small anisotropy $|T_\parallel - T_\perp| \ll T_\parallel$. For a great plasma anisotropy the quantity $\Delta N/N$ may be substantially greater, at least $T_\parallel^2/T_\perp^2 \sim 25$ times. These estimates are also in sharp contradiction with the experiment.

**** T H E E N D ****

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